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ORLANDO, FLORIDA

PROCEEDINGS

Evaluation of Environmentally Acceptable Protection Schemes for High Strength Steel Fasteners

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Accelerated corrosion tests were carried out to assess the performance of selected coated fastener assemblies representative of those used in the M1 Abrams tank and Bradley fighting vehicle The samples consisted of various coatings on grade 8 steel bolts inserted through/into armor steel or Al 5083 blocks. The coatings tested included currently used electroplated Cadmium as well as IVD (Ion Vapor Deposited) Aluminum, and a proposed binary, Zn-Ni electroplate. The effects of co-mingling electroplated Cadmium with the other coatings utilized in the test assemblies were determined. Salt spray testing was performed in accordance with ASTM B117. In addition, salt water immersion tests were performed with continuous monitoring of the electrochemical potential. Breakaway torque values obtained after completion of either immersion or salt spray tests were compared against coefficient of friction measurements taken from the scratch tests.

Cadmium electroplate exhibited excellent corrosion protection for grade 8 steel bolts in salt spray or immersion tests. The IVD Aluminum (chromated) and Zn-Ni coatings were the best overall alternatives to Cadmium plate. Co-mingling of Cadmium with the other coatings did not create significant galvanic corrosion problems. Loosening of the Zn-Ni alloy plated fasteners will not likely occur if torque values specified for Cd plate are used. Breakaway torque values were proportional to the respective coefficient of friction measurements from scratch tests for all but the IVD Aluminum coated specimens.

Background

Initial corrosion testing was done by ARL Materials Directorate in 1991 in a TACOM (Tank/Automotive Command) sponsored study to determine the effects of substituting Zinc or various other coating systems in the place of electroplated Cadmium. In addition to test assemblies utilizing a single coating, mixed assemblies comprised of various coated bolts and Cadmium coated washers/nuts were evaluated. The results were published in a technical report (MTL TR 92-40),[1] which contains complete corrosion data and photographic documentation of the corrosion observed throughout the test program for Cd, Zn-Ni, Zn OD (Olive Drab finish), Zn-Co, Sn-Zn, and modified phosphate coatings. This paper will summarize these results, and add data for IVD Al. Three types of IVD Al are compared against the Cadmium and Zn-Ni plating.

Program Outline

The test program and fasteners assemblies were developed by G. MacAllister, TACOM (retired), and M. Levy, ARL-MD (retired). The test assemblies consist of sections of actual armor plate and the coatings tested are described in more detail in the following section. The two methods of testing used on the assemblies were saltspray, and 3.5% saltwater immersion in which E-corr values were measured vs. time.

Materials

All bolts were fabricated of SAE Grade 8, J429 steel, HRC 33-39 (Figure 1) and meet the requirements of MS-90728.

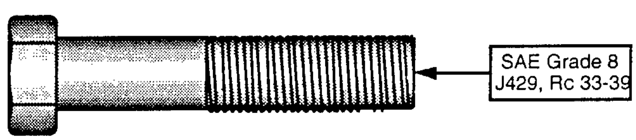


Figure 1 - Grade 8 Test Bolt

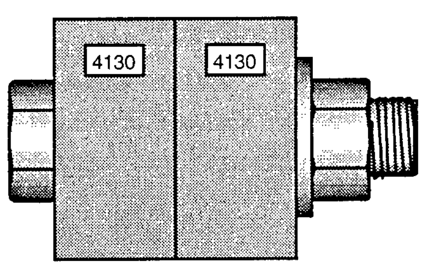


Figure 2 - Joint A Assembly

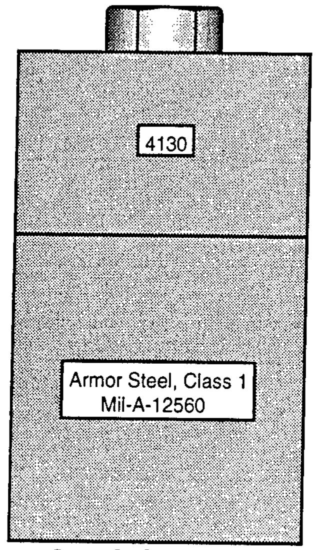


Figure 3 - Joint B Assembly

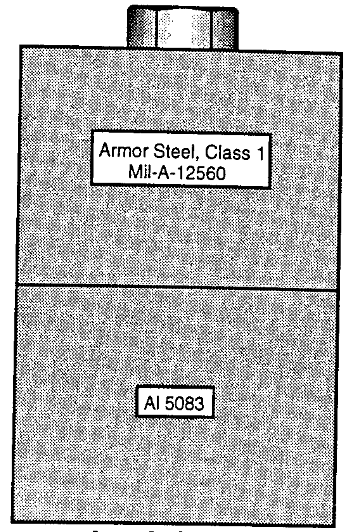


Figure 4 - Joint C Assembly

In material and dimensions, the nuts and washers were compatible with the grade 8 bolts. The two blocks in (assembly) Joint A (Figure 2) are fabricated of SAE Grade 4130 steel, HRC 30. The Joint B blocks (Figure 3) use armor steel described in MIL-A-12560, class 1 (HRC 28-33) in conjunction with 4130 steel . The Joint C assemblies use Aluminum alloy Al 5083 with 12560 armor steel. Chemical analysis of the armor alloys utilized is shown in Table 1.

Table 1 - Chemical Analysis of Test Blocks

Alloy	C	Mn	P	S	Si	Cr	Ni	Mo	V
4130	0.32	0.49	0.013	0.002	0.23	0.97	0.09	0.23	<0.01
Mil-A-12560	0.28	1.36	0.016	0.001	0.23	0.12	0.09	0.47	<0.01
Al 5083	*	0.55	*	*	<0.15	0.10	<0.05	*	*

Alloy	B	Fe	Cu	Mg	Ti	Sn	Zn	Al
4130	<0.0005	base	*	*	*	*	*	*
Mil-A-12560	0.002	base	*	*	*	*	*	*
Al 5083*	*	0.35	<0.05	4.2	<0.15	<0.05	<0.09	base

* Denotes alloying elements not measured

Coating Parameters

Cadmium plating was performed by Cadillac Plating Corp and processed in accordance with QQ-P416 Type II Class 3 and baked with a minimum thickness of 0.0002 in. FMC processed the Zn-Ni plating in accordance with their proposed specification covering the requirements for electrodeposited zinc-nickel alloy plating Class 3, Type II, minimum thickness 0.00030 in. The Zn-Ni alloy plate is 6-20% Ni. The IVD Al coating was processed at Anniston Army Depot, Anniston, AL. Pressure, wire feed rate, and current density were all held constant. The rack speeds and number of passes varied. The first run of specimens post treated with the sodium chromate treatment had a deposition period of 25 min and a measured thickness of 24.7 mils. The following two runs, IVD Al only, and IVD with Ni acetate treatment, both were deposited for about 12 min and measured 2.8 and 3.0 mils respectively.

Experimental Procedure

Accelerated corrosion tests were carried out to assess the performance of the coated fasteners described above. Salt fog testing was performed in accordance with ASTM B117. Observations were made and recorded every 24 hours of exposure up to 312 hours. The salt spray specifications for currently used electrodeposited coatings of Zinc and Cadmium require that these treatments shall show neither their white corrosion products nor basic metal corrosion products at the end of 96 hours of salt spray exposure. Identical specifications were applied for Ion Vapor Deposited Al. Due to a shortage of test blocks, the IVD Al, and IVD w/Ni acetate were not tested in saltspray (when sufficient test blocks are prepared, saltspray tests will be conducted). In addition, salt water immersion tests (3.5% NaCl solution) were performed in a circulating bath at 25°C with continuous electrochemical potential measurements (see Figure 5) and visual examinations made every 24 hours up to 312 hours of exposure.

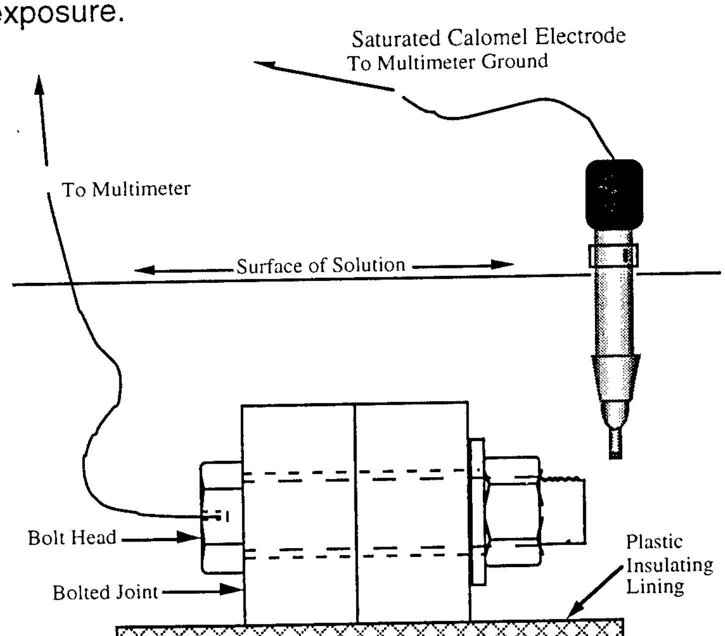


Figure 5 - Immersion Bath Setup

The electrical contact was made at the bolt head by drilling a small hole in its center and then soldering in an insulated wire. Silicone sealant was used to prevent erroneous readings caused by electrochemical interactions with the solder or wire (Figure 6). Photographs of the fastener assemblies were taken before and after testing to show the degree of corrosion developed. The coefficient of friction of the various platings were determined by the CSEM Revetest Scratch Tester, where a moving diamond stylus "scratches" the plated surface under either constant or linearly increasing load. This instrument is equipped with an integrated optical microscope, an acoustic emission detection system and a device to measure the tangential frictional force (in the scratching direction), from which the coefficient value is determined. Breakaway torque values for Joints A, B, C were obtained after either immersion or salt spray tests were completed.

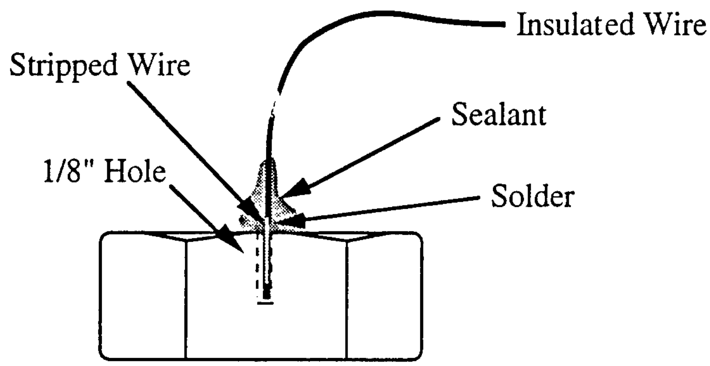


Figure 6 - Close up of immersion test bolt head

Results

For a high strength fastener used in a corrosive environment, a series of certain traits is desired. The protective coating, must be inexpensive, thin, uniform, and anodic with respect to the substrate material while not being so anodic that hydrogen assisted cracking may result. Electroplated Cadmium easily meets these criteria. However, because of the potential health risks posed by Cadmium, alternative coatings must be identified. Further, the "environmental acceptability" of any potential protective coating must also be considered an important selection criteria. All of the other coating materials tested are considered environmentally acceptable alternatives to Cd plating.

Salt Spray, Controls

The control assembly was used to observe the corrosion behavior of the bolt, nut, and washer without the influence of the joint assemblies. Table

2 contains observations made for the various coated control assemblies as a function of exposure time. Supporting photographs are contained in Appendix A, Figures I-III. The Cadmium coated components and chromate treated IVD Al showed no evidence of corrosion products (white or red rust) even after 312 hours (13 days) of exposure (Table 2, Figures I & II). The performance of the Zn-Ni coating, the first of a series of newer coatings being evaluated for military applications, is described in Table 2 and shown at 312 hours in Figure III. This coating protected the bolt, nut and washer assembly for 192 hours (8 days) although some staining was observed after 96 hours of exposure. White corrosion products appeared between 216-312 hours. Though not as good as the Cd or the thick chromated IVD Al, the Zn-Ni is superior to all previously studied Zn and Zn alloy coatings. In summary, the coatings may be ranked in the following order of decreasing protection: Cd and IVD Al (chromated), Zn-Ni. Clearly Cadmium and chromated IVD Al were the best performers.

Salt Spray, Joint A

The Joint A assembly has been described in Figure 2. Note that both blocks of the assembly were fabricated of 4130 steel. For each assembly the bolt, washer and nut were coated with the same material. Table 2 summarizes observations made as a function of time exposure for a total of 312 hours. Figures IV-VI, Appendix A, contain supporting photographic evidence. Cadmium plate and IVD Al (chromated) again were the best performers (no corrosion products 312 hours) followed by Zn-Ni. The Zn-Ni plate (shown at 312 hours) showed no evidence of white corrosion products for 120 hours of exposure.

A Zn-Ni coated bolt was tested with a Cadmium plated nut and washer in joint A in order to create a potential galvanic corrosion problem. Visual observations showing the results of exposing such assemblies to salt spray are contained in Table 2 and Figure VII. A comparison of the results contained in Table 2 show the Cadmium plated nut and washer on the mixed assembly with Zn-Ni were largely unaffected by the galvanic coupling. There appeared to be little effect of the Cd on the Zn-Ni plated bolt since it remained free of corrosion products for 96 hours.

Time (hours)	Controls				Joint A			
	A	B	C	D	A	B	E	C
6	N	N	N	N	N	N	N	N
24	N	N	N	N	N	N	N	N
48	N	N	N	N	N	N	N	N
72	N	N	N	N	N	N	N	N
96	N	N (Stains)	N	N	N	N	N	N
120	N	N (Stains)	N	N	N	N	2% WP on Bolt Head	N
144	N	N (Stains)	N	N	N	5% WP	5% WP, Cd Unaffected	N
168	N	N (Stains)	N	N	N	5% WP with YGS in Crevice	5% WP, YGS Cd unaffected	N
192	N	N	N	N	N	5% WP with YGS in Crevice	5% WP, YGS Cd unaffected	N
216	N	20% WP	N	N	N	30% WP with YGS in Crevice	20% WP, YGS Cd unaffected	N
240	N	20% WP	N	N	N	30% WP with YGS in Crevice	25% WP, YGS Cd unaffected	N
312	N	20% WP	N	N	N	35% WP with YGS in Crevice	40% WP, YGS Cd unaffected	N

Abbreviation Legend:

A - Cd Plated
B - Zn-Ni Plated
C - Chromated IVD Aluminum
D - Chromated IVD Al Bolt with Cd Nut
E - Zn-Ni Plated Bolt with Cd Nut
YGS - Yellow-Green Stains
WP - White Products
N - No Corrosion

Table 2 - Saltspray Observations, Control and Joint A Assemblies

Salt Spray, Joint B

The Joint B assembly has been described in Figure 3. The two blocks employed in this assembly were fabricated of 4130 steel and Armor Steel, Class 1 (MIL-A-12560). For each assembly the bolt, washer and nut were coated with the same material. Table 4 summarizes the observations made as a function of exposure time. Accompanying photographs, taken at 312 hours are contained in Figures VIII-X. The coatings may be ranked in the following order of decreasing merit: Cd - IVD Al (chromated), Zn-Ni. The Cadmium and IVD Al (chromated) provided protection for 312 hours of exposure. The Zn-Ni showed white zinc oxide corrosion products but no visible rust at 312 hours.

Salt Spray, Joint C

This Joint C assembly has been described in Figure 4. Note the different compositions of the two blocks in the assembly; Armor steel and Al 5083. For each assembly tested, the bolt, nut and washer were coated with the same material. Table 4 summarizes observations made for each coating as a function of exposure time. Figures XI-XIII, Appendix A, (312 hours) contain corresponding photographs. There was no evidence of white corrosion products or rust for either the Cd or IVD Al (chromated) coated assemblies throughout the 312 hours. Zinc-Nickel coatings were free of white corrosion products for 96 hours. White corrosion products appeared thereafter increasing with increasing time of exposure. These coatings may be ranked in the following order of decreasing merit, based on a total exposure time of 312 hours: Cd, tied with IVD Al (chromated), followed by Zn-Ni.

Time (hours)	Joint B A	Joint B B	Joint B C	Joint C A	Joint C B	Joint C C
6	N	N	N	N	N	N
24	N	N	N	N	N	N
48	N	N	N	N	N	N
72	N	N	N	N	YGS in the Crevice	N
96	N	YGS in the Crevice	N	N	YGS in the Crevice	N
120	N	30% WP with YGS in the Crevice	N	N	1% WP with YGS in the Crevice	N
144	N	30% WP with YGS in the Crevice	N	N	3% WP with YGS in the Crevice	N
168	N	25-35% WP with YGS in the Crevice	N	N	3-5% WP with YGS in the Crevice	N
192	N	40% WP with YGS in the Crevice	N	N	5% WP with YGS in the Crevice	N
216	N	40% WP with YGS in the Crevice	N	10% Chromate Breakdown, no rust	5% WP with YGS in the Crevice	N
240	N	40% WP with YGS Covering 40% of Bolt	N	40% Chromate Breakdown, no rust	10-15% WP with YGS Covering 40% of Bolt	N
312	N	65% WP with YGS and YGS	N	50% Chromate Breakdown, no rust	50% WP with pink stains in crevice due to misfit of Blocks.	N

Abbreviation Legend:

A - Cd Plated
B - Zn-Ni Plated
C - Chromated IVD Aluminum

WP - White Products
N - No Corrosion
YGS - Yellow-Green Stains

Table 2 - Saltspray Observations, Joint B and Joint C Assemblies

3.5% NaCl Immersion - Controls

Figure 7 contains plots of potential measurements made for the coated control assemblies during the course of their immersion in 3.5% NaCl solution. Though not rate sensitive, this technique will show "breakdown" or "loss of protection" when the corrosion potential changes from the base value of the coating towards that of uncoated steel. Photographs of the coated control assemblies after immersion for 312 hours complement the potential time data (Figures XIV-XIX).

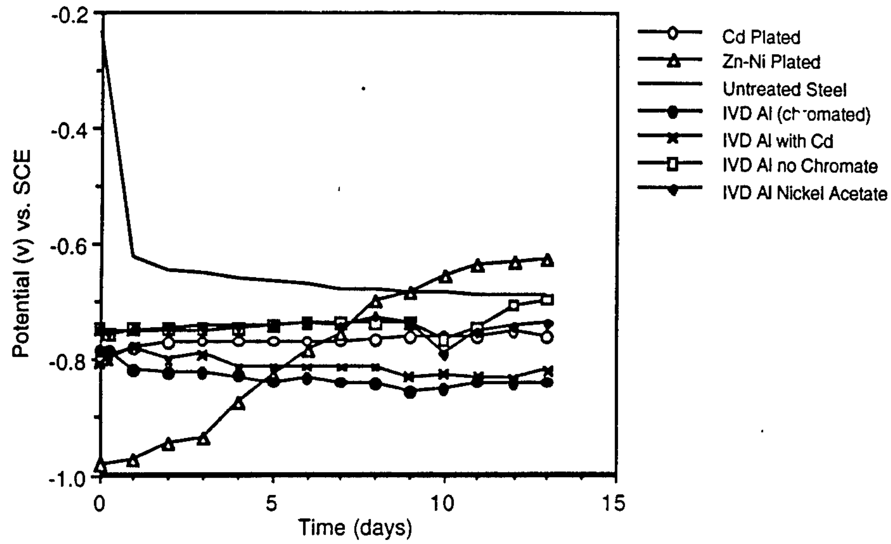


Figure 7 - Potential vs. Time
3.5% NaCl Immersion - Controls

Referring to Fig. 7, the potential of the uncoated steel drops markedly in the more active direction (from -0.231 to -0.624) within a 24 hour period indicative of the onset of corrosion which is confirmed by the first appearance of rust. The changes in potential thereafter are minimal and a fairly constant potential (-0.675) is achieved after 7 days of exposure when 50% of the steel surfaces are covered with rust. If the potentials of the coated parts approach or attain this potential then the coating has "broken down" and is no longer cathodically protecting the steel. The Zn-Ni coating shows a moderate rate of change of potential approaching the potential of corroding steel after 9 days of immersion time. In contrast, the potential of the Cadmium plated parts remains relatively constant (-0.76) throughout the 312 hours of immersion and provides the best protection for the steel substrate. The potentials and coating performances of the IVD Al assemblies correlated with the thicknesses of the IVD coatings. In the case of the chromated IVD Al, the extremely thick (24.7 mil) coating most greatly contributed to the favorable stable behavior similar to the behavior of the Cadmium plate. When mixed with a Cadmium nut, the thick IVD assembly behaved similar to the unmixed specimen although it shifted to slightly more noble behavior. In contrast to the thick, chromated IVD Al, the thin IVD (3 mils) coatings, (with and without the Ni acetate), the zone of stable E-corr values decayed after about 168 hours (7 days). This fluctuation corresponded with the loss of coating and the appearance of rust. While both thin IVD coatings showed heavy rust, the nickel acetate treated control assembly retained a few patches of coating after 312 hours. The coated control assemblies may be ranked in the following order of decreasing merit: Cd, chromated IVD Al, Zn-Ni, IVD Al with Ni acetate, and untreated IVD Al.

Immersion - Joint A

All possible Joint A coupling schemes were not tested due to the limited number of test blocks available. Potential measurements and observations were made during the course of immersion testing of the coated Joint A assemblies. Their potentials are plotted as a function of time in Figure 8.

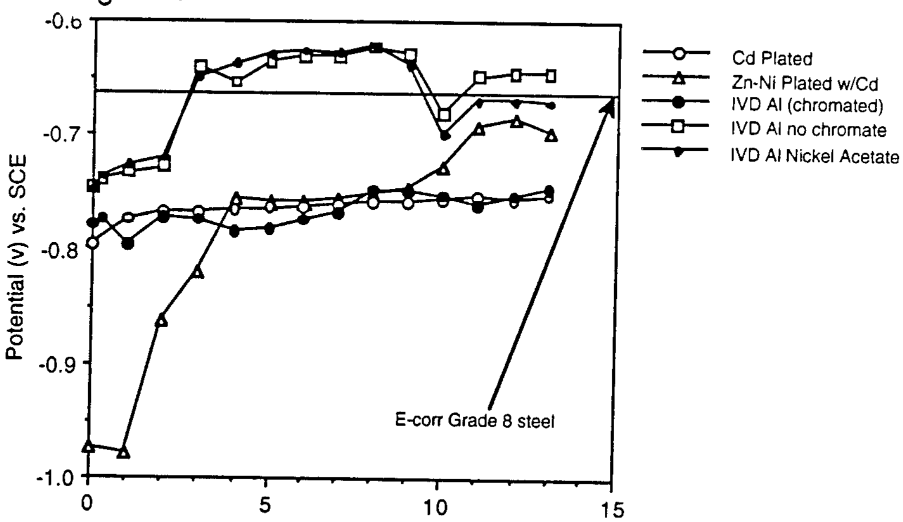


Figure 8 - Potential vs. Time
3.5% NaCl Immersion - Joint A

Complementary photographs at 312 hours of immersion are shown in Figures XX-XXV: Appendix B. The potential of the Cadmium coated assembly remained relatively stable throughout the entire test, indicative of its excellent corrosion resistance. The Zn-Ni plated bolt with Cd washer and nut exhibited very little rust on the bolt and washer after 12 days of immersion. This coincided with the potential stabilizing to that of Cadmium after an initial rapid increase over the first two days to the Cadmium potential. A gradual rise in potential beginning between 9 and 10 days culminating with the appearance of rust indicated that the Cd coating on the nut and washer had broken down. The IVD Al specimens again displayed performance that was dependent upon coating thickness. In the case of the thick chromated IVD Al, E-corr measurements, while somewhat less stable, slowly increased from (-0.775) to (-0.750) similar to the values recorded for Cd. The two thin IVD coatings began negative with respect to steel at around (-0.75) and rapidly climbed to the potential of steel within 96 hours. Aluminum sacrificial products were not visible as in the Zinc plated fasteners as they either dissolved or were carried away in the circulation of the bath. At the 96 hour mark all that was visible was red rust with a few small patches of IVD Al which disappeared and were replaced by rust after 120 hours. The coated Joint A assemblies may be ranked in the following order of decreasing merit: Cd, chromated IVD Al, Zn-Ni with Cd washer and nut; IVD Al (no treatment), IVD Al with nickel acetate.

Immersion - Joint B

For these joint assemblies, potential-time curves are plotted in Figure 9, and corresponding photographs are contained in Figures XXVI-XXX.

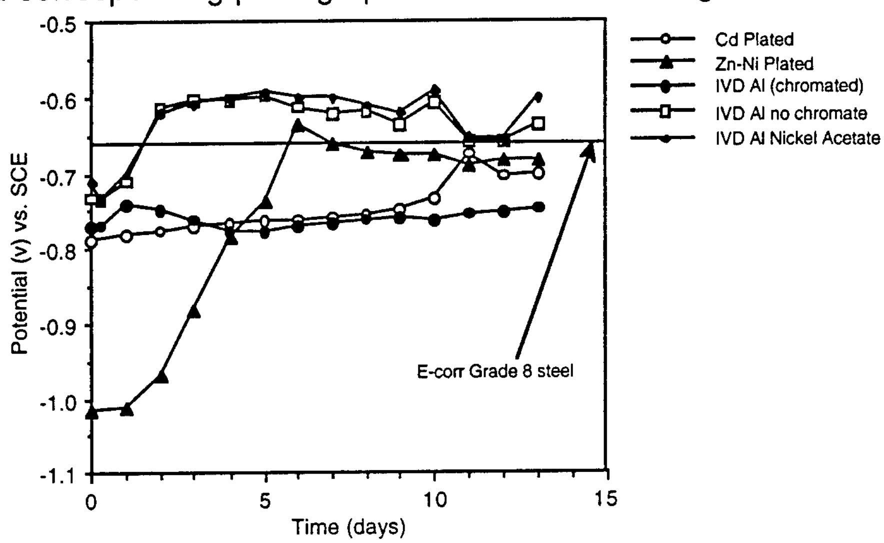


Figure 9 - Potential vs. Time
3.5% NaCl Immersion - Joint B

It should be noted that Cd washers were not incorporated in the assemblies due to the unavailability of additional steel blocks. The potential for the Cd plated joint was relatively stable for 10 days and then increased to the steel potential as rusting of the edges of the Cd plated washers was observed. The Cd plated bolt was free of corrosion products. The Zn-Ni plated joint reached the steel potential after 5 days immersion time when rust was observed on the washers. The IVD Al specimens displayed behavior similar to data observed in joint A, with a strong dependence on coating thickness. In the case of the thick chromated IVD Al, E-corr measurements remained relatively stable, settling in at (-0.76) after an initial peak at (-0.73) at the 24 hour mark. With zero visible rust after 312 hours, the thick chromated IVD Al was able to provide equal to better performance than Cd. The two thin IVD coatings which began negative with respect to steel at around (-0.73), rapidly climbed to the potential of steel within 96 hours. Again Al sacrificial products were not visible. With no trace of the thin IVD coatings visible at 96 hours, corrosion of the steel bolt substrate was characterized as even more severe than the rusting observed on joint A. Due to the gross rusting present, an assessment as to which thin IVD coating performed better was not possible. The ranking of these coatings for Joint B in decreasing order of protection is: Chromated IVD Al, Cd, Zn-Ni, IVD Al (no treatment) tied with IVD Al, nickel acetate.

Immersion - Joint C

Armor steel and Al 5083 blocks were used in this assembly. Again because of the limited number of blocks available Cd washers were not incorporated in assemblies containing the other coatings. Plots of potential as a function of immersion time are shown in Figure 10.

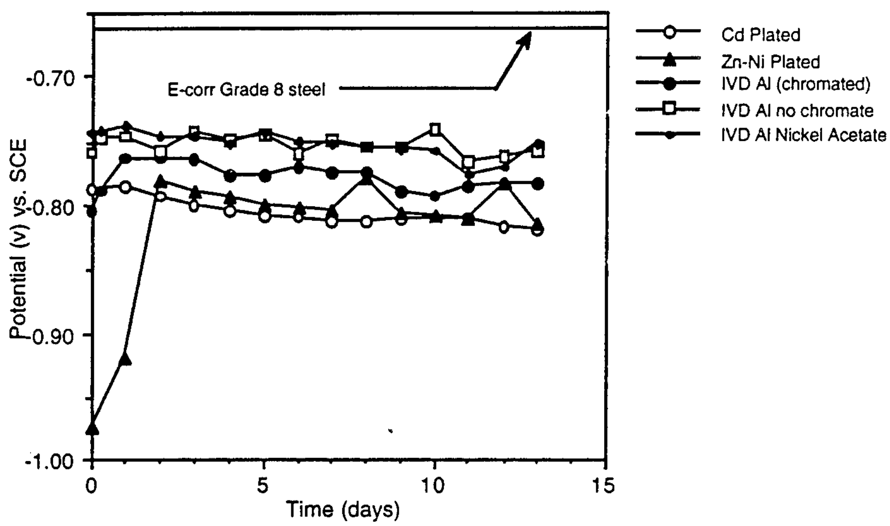


Figure 10 - Potential vs. Time
3.5% NaCl Immersion - Joint C

A photograph representitive of each coating after 312 hours is Figure XXXI. The Cadmium potential was relatively stable throughout the test and showed no evidence of corrosion. The potential of the Zn-Ni coating approached the potential of Aluminum within a three day period when white corrosion products formed. There was little or no evidence of rust on any of the assemblies at the conclusion of the test with the exception of the thin IVD Al coatings which displayed moderate rusting of about 10% of the total surface area. The observed moderation in corrosion severity was due to the presence of the Al 5083 block found in Joint C. The Al 5083 is anodic to steel, and provides additional cathodic protection. Cadmium again is the best performer followed by chromated IVD Al @ 24.7 mils, Zn-Ni, Sn-Zn, IVD Al and IVD Al with Ni acetate @≈ 3.0 mils.

Breakaway Torques

Tables 4 and 5 contain breaking torque values for the various joints which were exposed to either Saltspray or immersion in chloride solution. It should be noted that the threaded portion of the bolt was lubricated with oil prior to assembly and torquing of each joint. Each joint was torqued to 180 ft. lbs. except for those joints involving the Zn-Ni coating where the initial torque was 90 ft-lbs. due to the smaller diameter of the bolt. For comparison, data from the previous report containing the other Zn and Zn alloy coatings is included.[1]

Table 4 - Saltspray Breakaway Torques

Joint A's

Fastener Coating	Breakaway Torque, As fraction of initial torque
Modified Phosphate	0.648
Modified Phosphate w/Cd Nut & Washer	0.741
Cd (BWN)	0.694
Zn OD (BWN)	0.879
Zn OD w/Cd Nut & Washer	0.741
Zn-Co (BWN)	0.926
Zn-Co w/Cd Nut &Washer	0.741
Zn-Sn (BWN)	0.833
Zn-Sn w/Cd Nut & Washer	0.833
Zn-Ni (BWN)*	0.833
Zn-Ni w/Cd Nut & Washer*	0.833
IVD Aluminum, (Chromated)	0.833

Joint B's

Fastener Coating	Breakaway Torque, As fraction of initial torque
Modified Phosphate	0.648
Cd	0.787
Zn OD	0.741
Zn-Co	0.926
Zn-Sn	0.787
Zn-Ni*	0.833
IVD Aluminum, (Chromated)	0.718

Joint C's

Fastener Coating	Breakaway Torque, As fraction of initial torque
Modified Phosphate	0.833
Cd	0.833
Zn OD	0.972
Zn-Co	0.926
Zn-Sn	0.926
Zn-Ni*	1.019
IVD Aluminum, (Chromated)	0.648

*Zn-Ni used smaller bolts with initial torquing at 90.0 ft-lbs

Generally the superphosphate coated joints exhibited significantly reduced breaking torques indicating the fastener could loosen during service. In most cases, the Zn and Zn alloy coatings exhibited breaking torques which were either comparable to or higher than Cadmium. Breaking torques measured for IVD Al were sometimes higher and sometimes lower than readings for Cd and are inconclusive. Generally little evidence of corrosioh was observed in the threaded portion of these coated bolts in the various joints and loosening in service is therefore not anticipated.

Table 5 - Immersion Breakaway Torques

Joint A's

Fastener Coating	Breakaway Torque, As fraction of initial torque
Cd (BWN)	0.787
Zn OD (BWN)	0.741
Zn OD w/Cd Nut & Washer	0.879
Zn-Ni w/Cd Nut & Washer*	0.741
IVD Aluminum, Anniston (Chromated) (BWN)	0.741
IVD Aluminum, Anniston (No Seal)(BWN)	0.694
IVD Aluminum, Anniston (Ni Acetate)(BWN)	0.787

Joint B's

Fastener Coating	Breakaway Torque, As fraction of initial torque
Modified Phosphate	0.602
Cd	0.741
Zn OD	0.972
Zn-Co	0.879
Zn-Sn	0.879
Zn-Ni*	0.741
IVD Aluminum, (Chromated)	0.833
IVD Aluminum (No Seal)	0.787
IVD Aluminum (Ni Acetate)	0.833

Joint C's

Fastener Coating	Breakaway Torque, As fraction of initial torque
Modified Phosphate	0.787
Cd	0.741
Zn OD	0.926
Zn-Co	0.926
Zn-Sn	0.833
Zn-Ni*	0.741
IVD Aluminum, (Chromated)	0.787
IVD Aluminum, (No Seal)	0.833
IVD Aluminum, (Ni Acetate)	0.972

*Zn-Ni used smaller bolts with initial torquing at 90.0 ft-lbs

Coefficient of Friction

The frictional force per unit contact area (frictional stress), F_t, between the nut and the washer, or that between the washer and the armor plate, whichever is lower, will guarantee that the assembly will remain fastened at the set level. This force F_t, is given by $F_t = \mu^* \sigma'$, where $\mu^* = \tan\phi$ is the friction coefficient between the two surfaces in contact and σ' is the normal, compressive stress within the nut and the part of the washer in contact with the nut. This stress is proportional to the tensile stress σ within the threaded rod (bolt).

The friction coefficient $\mu^*=\mu_a + \mu_p$, where μ_a and μ_p are the adhesive and ploughing components, respectively. The adhesive component depends on the intrinsic nature of the coating, namely on atomic bonding, chemistry and mutual solubility between coating and substrate materials and the ploughing component depends on surface roughness and the stress required to shear surface asperities. The friction coefficient was determined by automatic scratch testing, using a 200μm radius diamond stylus, a loading rate dL/dt=100 N min^{-1}, a scratching speed dx/dt=1` mm min^{-1}, hence a load gradient dL/dx=10 N mm^{-1}, where L (N) is applied normal load within the 0-60 N range, x (mm) is the distance and t (min) is time. Average coefficient of friction values μ^* are listed in table 7 for the included coatings as well as coatings from the prior study. If F_t is the friction stress required to maintain an appropriate fastening, and two coatings, for example Zn and Cd, are compared, then:

$$F_t = \mu^*_{Zn}\,\sigma'_{Zn} = \mu^*_{Cd}\,\sigma'_{Cd} = \mu^*_i\,\sigma'_i \qquad (1)$$

where μ^*_{Zn} and μ^*_{Cd} and μ^*_i are the coefficients between two Zn, two Cd or two "i" metal coatings, respectively, and σ'_{Zn}, σ'_{Cd}, σ'_i are the respective compressive stresses within the Zn-coated, Cd-coated and "i" metal-nuts. The proportionality between compressive stresses within the nuts and the respective tensile stesses within the bolts, σ_{Zn} and σ_{Cd}, may be expressed by:

$$\sigma'_{Zn} / \sigma'_{Cd} = \sigma_{Zn} / \sigma_{Cd} \qquad (2)$$

hence,

$$\mu^*_{Zn}\,\sigma_{Zn} = \mu^*_{Cd}\,\sigma_{Cd} \qquad (3)$$

These friction coefficients are not readily measurable, whereas those between the diamond stylus and the two coatings are. The ratios of the two groups of coefficients may be assumed to be approximately equal. Hence:

$$\mu^*_{Zn\text{-}Zn} / \mu^*_{Cd\text{-}Cd} = \mu^*_{Zn\text{-}dia} / \mu^*_{Cd\text{-}dia} \qquad (4)$$

In the present case, see Table 7 for virgin, as-coated specimens μ^*_{Zn}=0.488 and μ^*_{Cd}=0.377, hence $\sigma_{Zn} = 0.772\sigma_{Cd}$. Thus the tension inside the Zn-coated bolt that maintains good fastening may be 22.8% lower than that inside the Cd-coated bolt and so may the required torque to achieve the same level of fastening. These conclusions remain valid, if we consider the various friction coefficients following salt-spray or immersion tests in chloride solution. Thus, for salt-sprayed specimens, (see Table 7) $\mu^*_{Zn} = 0.551$ and $\mu^*_{Cd} = 0.447$, and $\sigma_{Zn} = 0.811\sigma_{Cd}$, and for chloride solution immersed specimens, $\mu^*_{Zn} = 0.424$ and $\mu^*_{Cd} = 0.330$, and $\sigma_{Zn} = 0.778\sigma_{Cd}$, hence the respective tensions inside the Zn-coated bolts that maintain good fastening may be 18.9% and 22.2% lower than those inside the Cd-coated bolts and so may the required torques to achieve the same level of fastening. Similar calculations show comparable reductions attributable to the following virgin coatings: Thick IVD Al (chromated) 39.4 %, Zn-Ni 22.8%, Zn-Co 15.3%, and Sn-Zn 11.7%. The thin IVD Al coatings, plain and with Ni acetate will require 12.2 and 20.8% higher torques respectively, to maintain the same level of fastening as the Cd plated parts. Superphosphate also required a higher torque of 11.2%. With the exception if the IVD Al fasteners these data complement and support the breakaway torque results; loosening of the Zn and Zn alloy coated fasteners will not occur when Cd torque values are used, whereas loosening of the superphosphate coated fastener will most likely occur. No consistant trend was apparent in the IVD Al data. The breakaway torque readings were inconsistent with the friction coefficients, and data measured for just the friction coefficients was inconsistent. Continued studies of IVD Al coatings should reveal more frictional data. Microscopic investigation by Kattamis revealed that in most cases, the platings exceeded the thickness requirements and were relatively uniform, contiguous and adherent.[2]

Table 7 - Average Friction Coefficients, μ^*, of Coated Specimens

Coating	Virgin	Salt Spray	NaCl Immersion
Zn-Ni	0.532	0.472	0.422
Zn-Co	0.445	0.467	0.496
Zn-Sn	0.427	0.287	0.406
Cd	0.377	0.[illegible]47	0.330
Modified Phosphate	0.355	0.286	0.237
Zn (OD)	0.488	0.551	0.424
IVD Al (chromated)	0.697 0.622*	no data	0.390
IVD Al	0.336	no data	0.290
IVD Al (w/Ni acetate)	0.312	no data	0.300
Steel Substrate	0.277	no data	no data

* After thinning from 24.7 mils to 3.1 mils

Discussion

In all test situations, the thick chromated IVD Al met or exceeded the corrosion resistance found in Cadmium plate and always outperformed Zn-Ni. While this performance level is impressive, it is not always practical from a coating thickness standpoint. All of the grade 8 fasteners tested used a coarse thread which allowed the use of the 24.7 mil IVD Al coating. An examination of the disassembled assemblies also showed that gauling had occured in the threaded regions. For high strength aerospace applications where a fine thread is used, thick coatings are impractical if not impossible. While Zn-Ni performance was not stellar, it met the 96 hour requirement in all cases with a much more reasonable 3 mil coating. For non-threaded applications and situations not requiring tight tolerances, IVD Al is a good replacement for electroplated Cd protective coatings.

Conclusions

(1) Cadmium exhibited the best corrosion per unit coating thickness protection for grade 8 steel bolts in salt spray and immersion tests.

(2) In situations where coating thickness is not an issue, IVD Al performs comparably to Cd in protection of steel.

(3) On a per unit coating thickness, Zinc-Nickel coating was the best overall alternative to Cadmium plate and met the corrosion resistance requirements for Zinc plating.

(4) Co-mingling of Cadmium with the other coatings in the Controls or Joint A showed little or no effect on Zn-Ni and thick chromated IVD Al coatings.

(5) The substitution of Al 5083 for one of the steel blocks in Joint C did not diminish the performance of Cd, chromated IVD Al , and Zn-Ni coatings when compared to both joints A + B and improved the performance of the thin IVD Al coatings.

(6) Loosening of the Zn-Ni or thick IVD Al coated fasteners will not likely occur when Cd torque values are used (under wet conditions).

Recommendations

(1) Use Zinc-Nickel plating as an alternative to Zinc plating.

(2) Continue to implement the TARDEC policy of using the torque values for fasteners which are currently provided in technical manuals regardless of co-mingling of Cd and Zn plated bolts.

(3) Continue investigating Cd plate alternatives including IVD Al in varying thicknesses with chromate and non-chromate treatments.

(4) Evaluate Cd plating alternatives for aerospace fasteners of high strength steels such as 4340 and Aermet ® 100.

References

1.) M. Levy, B. Placzankis, R. Brown, R. Huie, and M. Kane, The Effects of Co-mingling Dissimilar Fastener Coatings on the Corrosion Behavior of Steel Bolt Assemblies, MTL TR 92-40, (July 1992)

2.) T.Z. Kattamis, R. Huie, J. Kelley, C. Fountzoulas, and M. Levy, Microstructure, Adhesion and Tribological Properties of Conventional Plasma-Sprayed Coatings on Steel Substrates. (Submitted for Publication in: Journal of Adhesion Science and Technology)

Appendix A
Saltspray Test Assemblies After 312 Hours

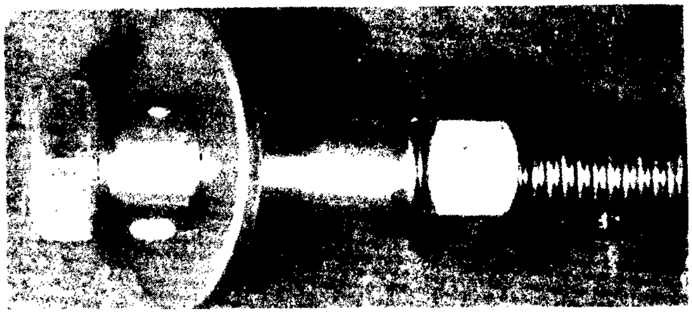


Figure I - Cd Plated Control

Figure II - Chromated IVD Al Control

Figure III - Zn-Ni Plated Control

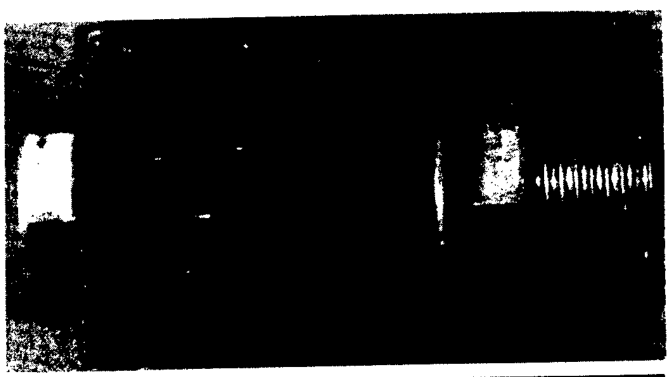


Figure IV - Cd Plated Joint A Assembly

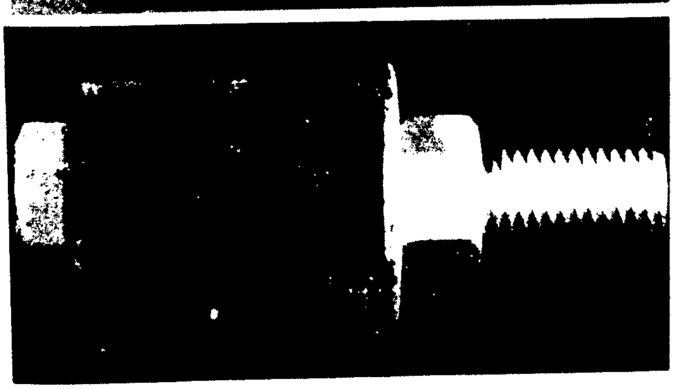


Figure V - Chromated IVD Aluminum Joint A Assembly

Appendix A (continued)
Saltspray Test Assemblies After 312 Hours

Figure VI - Zn-Ni Plated Joint A Assembly

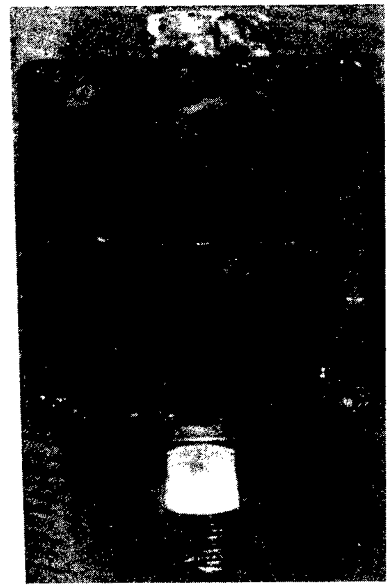
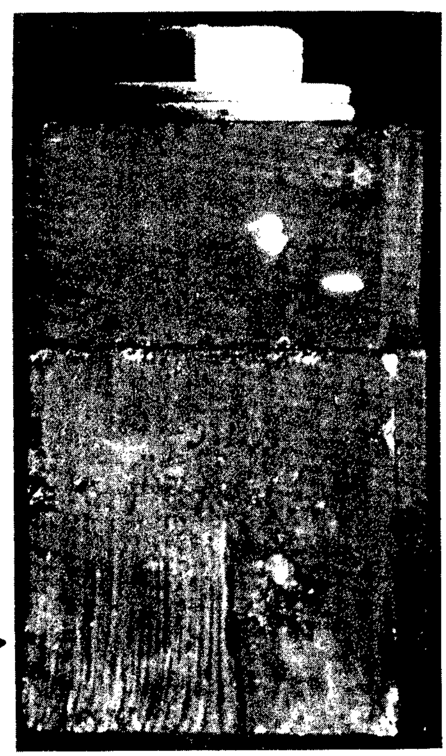


Figure VII - Zn-Ni Plated Joint A Assembly Mixed with Cd

Figure VIII - Cd Plated Joint B Assembly

Figure IX - Chromated IVD Al Joint B Assembly



Appendix A (continued)
Saltspray Test Assemblies After 312 Hours

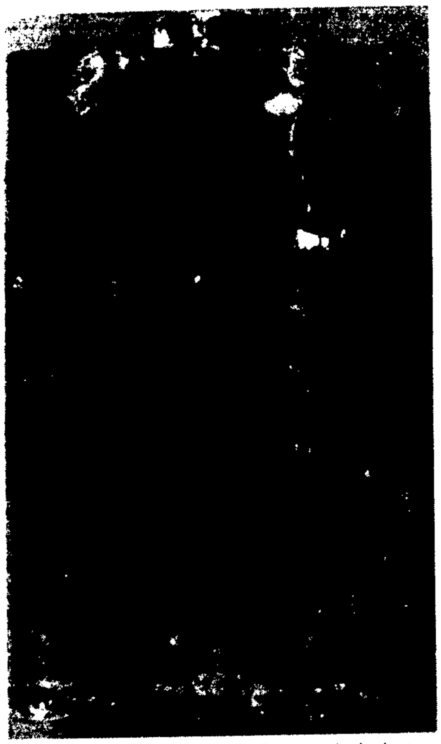


Figure X - Zn-Ni Plated Joint B Assembly

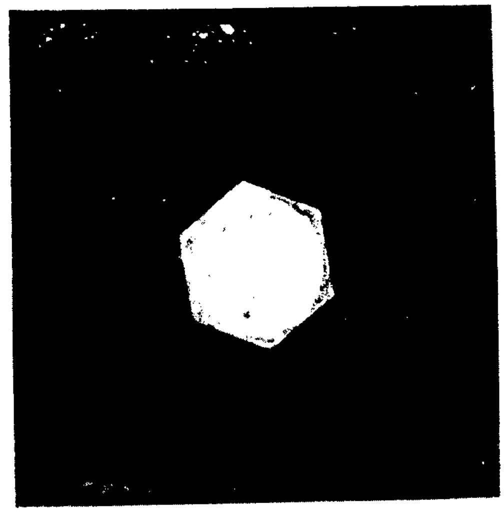


Figure XI - Cd Plated Joint C Assembly

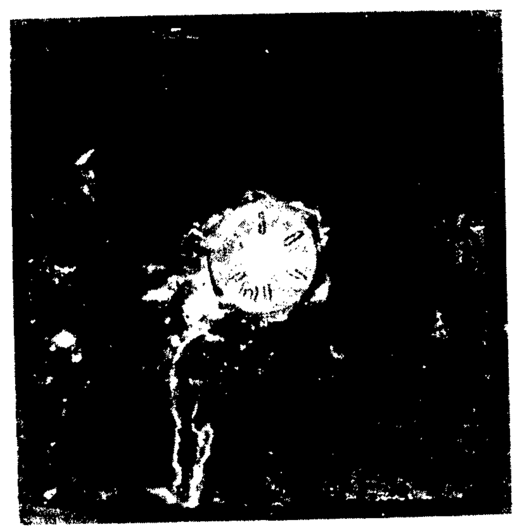


Figure XII - Zn-Ni Plated Joint C Assembly

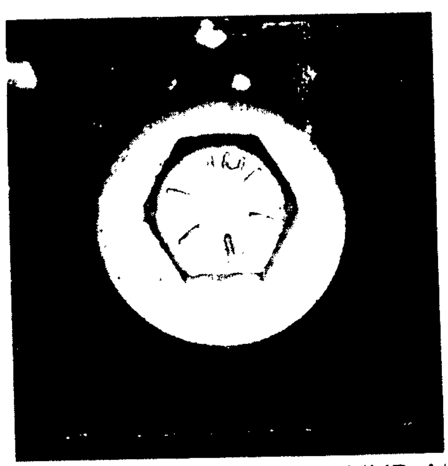


Figure XIII - Chromated IVD Al Plated Joint C Assembly

Appendix B
Immersion Test Assemblies After 312 Hours

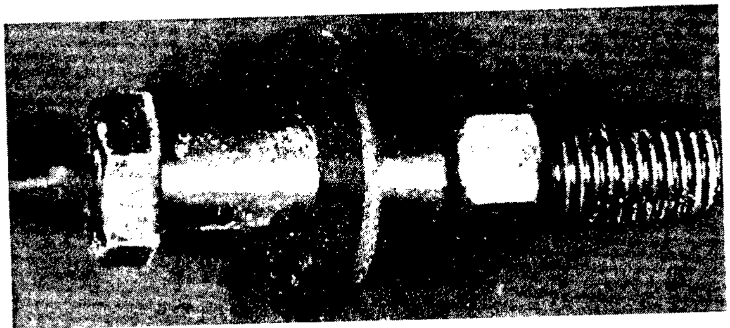


Figure XIV - Cd Plated Control

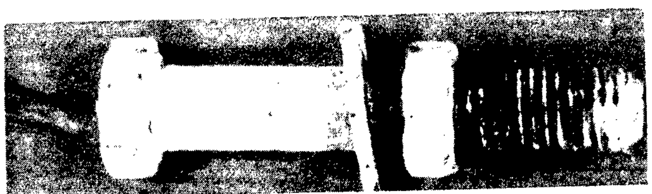


Figure XV - Zn-Ni Plated Control

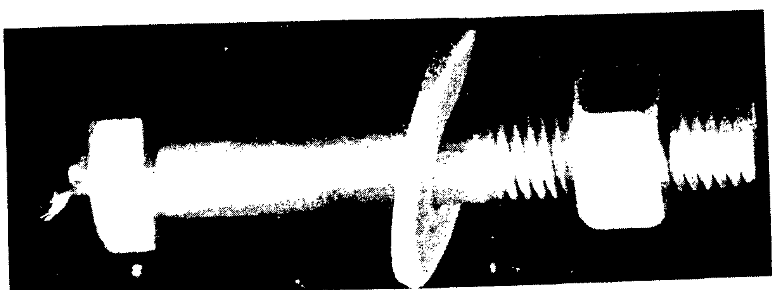


Figure XVI - Chromated IVD Al Control

Figure XVII - Chromated IVD Al Control
with Cd Nut

Appendix B (continued)
Immersion Test Assemblies After 312 Hours

Figure XVIII - IVD Al (3 mil, No Treatment)

Figure XIX - IVD Al (3 mil, Ni Acetate Treated)

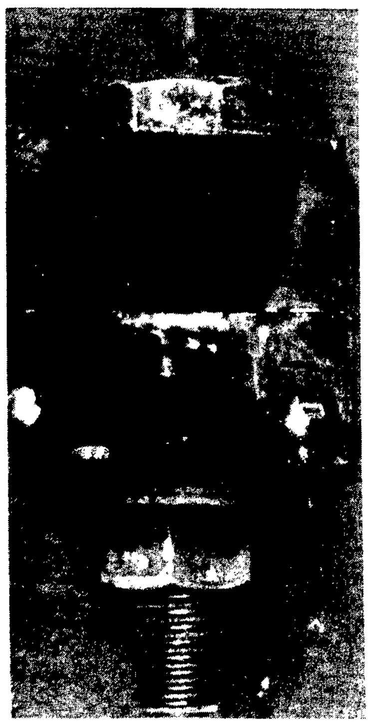


Figure XX - Cd Plated Joint A Assembly

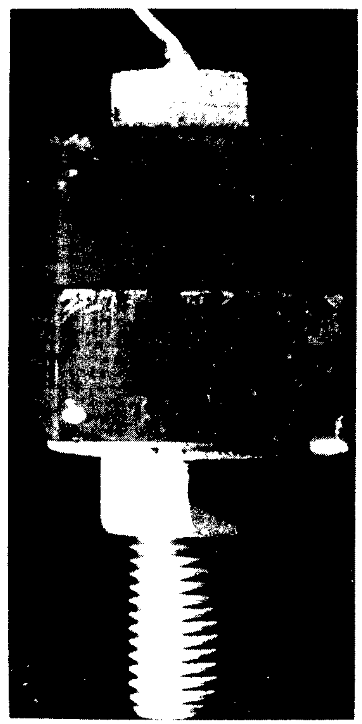


Figure XXI - Chromated IVD Al Joint A Assembly

Appendix B (continued)
Immersion Test Assemblies After 312 Hours

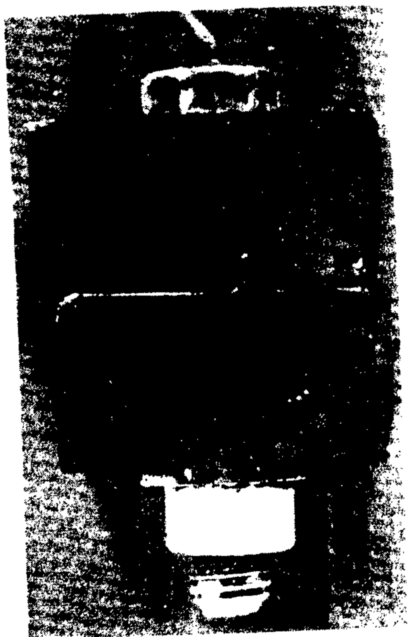


Figure XXII - Zn-Ni Plated Joint A Assembly

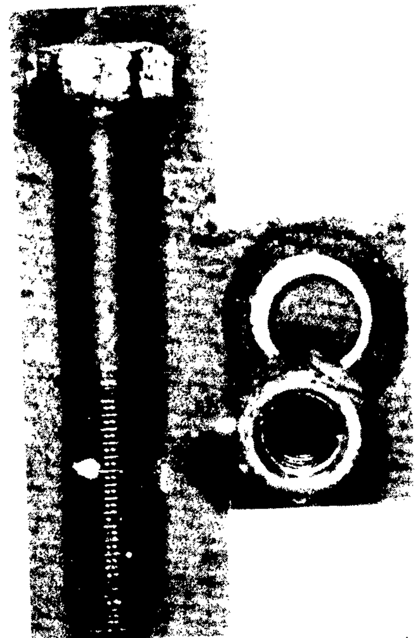


Figure XXIII - Zn-Ni Plated Joint A Assembly. Mixed with Cd. Disassembled to Show Amounts of Corrosion

Figure XXIV - IVD Al (3 mil, No Treatment) Joint A Assembly

Appendix B (continued)
Immersion Test Assemblies After 312 Hours

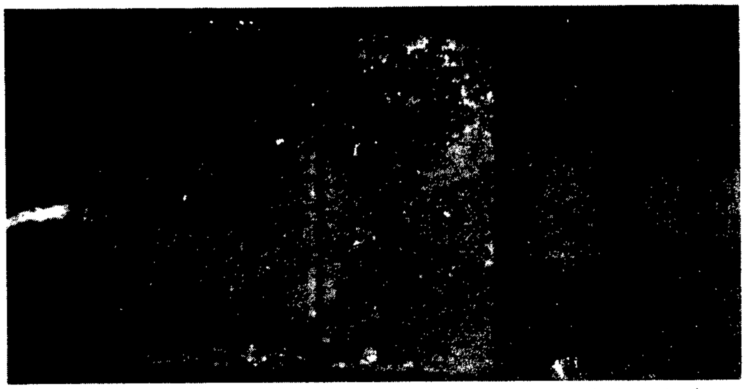


Figure XXV - IVD Al (3 mil, Ni Acetate Treated) Joint ^ Assembly

Figure XXVI - Cd Plated Joint B Assembly

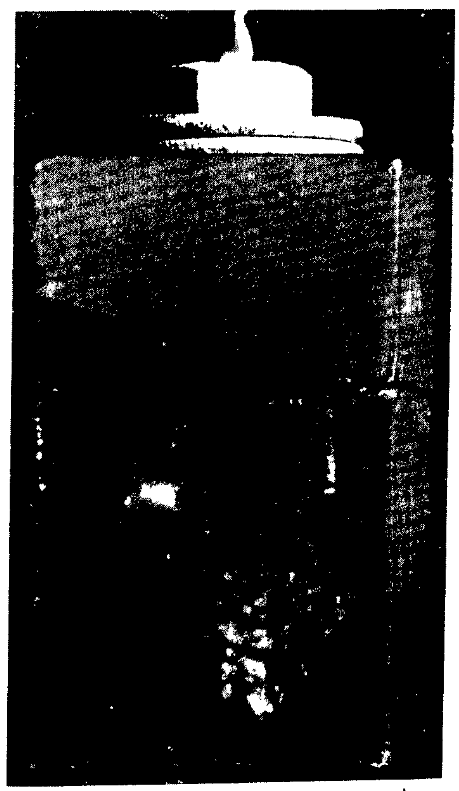


Figure XXVII - Chromated IVD Al Joint B Assembly

Appendix B (continued)
Immersion Test Assemblies After 312 Hours

Figure XXVIII - Zn-Ni Plated Joint B Assembly

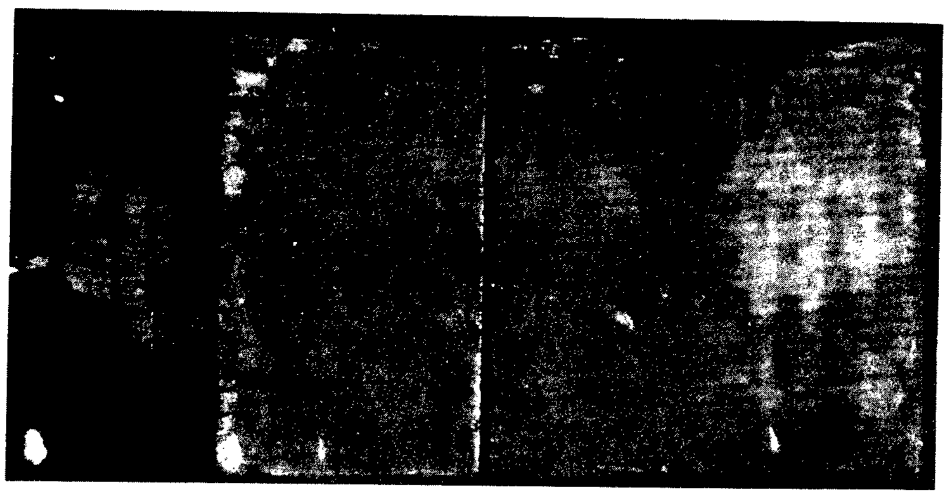


Figure XXIX - IVD Al (3 mil, No Treatment), Joint B Assembly

Appendix B (continued)
Immersion Test Assemblies After 312 Hours

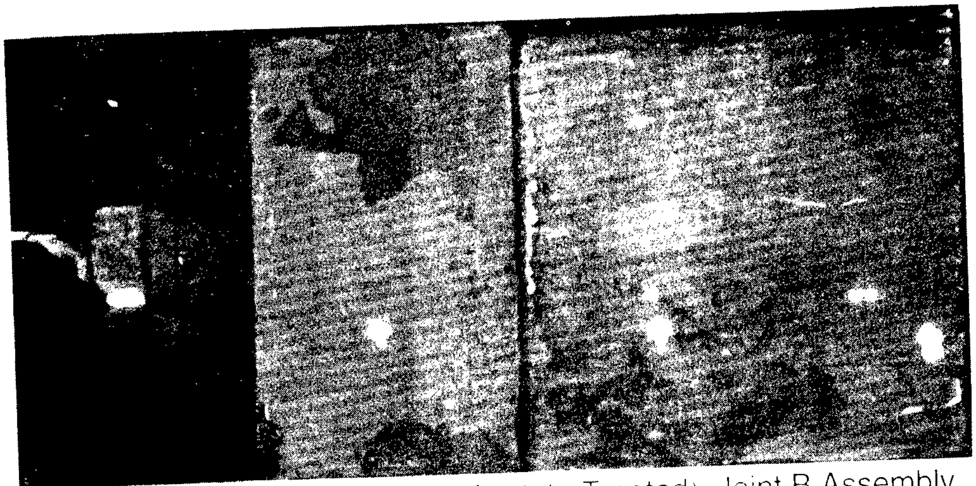


Figure XXX - IVD Al (3 mil, Ni Acetate Treated), Joint B Assembly

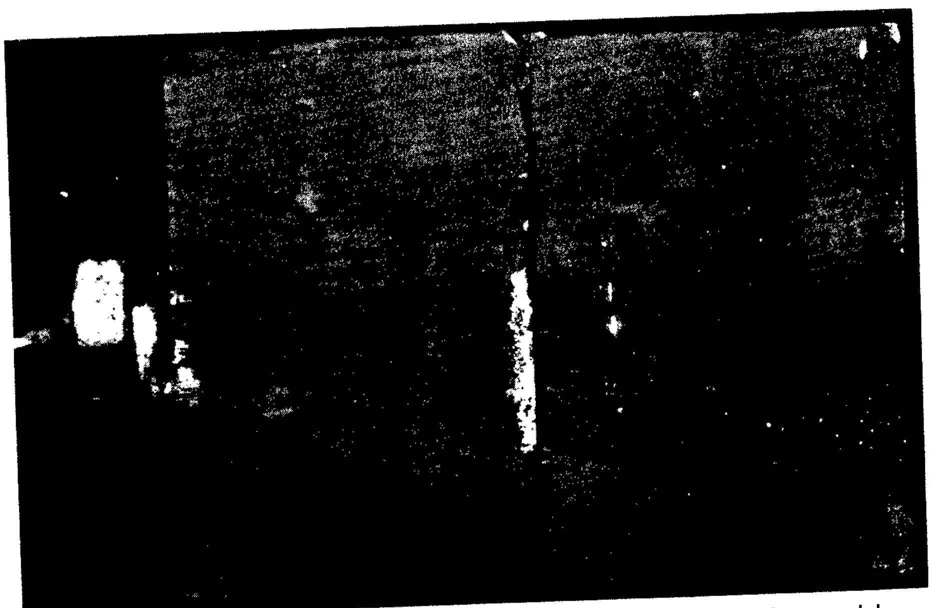


Figure XXXI - IVD Al (3 mil, No Treatment), Joint C Assembly Showing Much Original Coating Intact, Cathodically Protected by the Large Al 5083 Block, as Observed in All Other Joint C Assemblies.